STRING THEORY

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Strasbourg

Outline

1) Quantum mechanics and general relativity : why gravity is different
2) String Theory : from strong interactions to gravity
3) Extra dimensions and Kaluza-Klein unification
4) D-branes and brane-world models
5) Conclusions

1) Quantum mechanics and general relativity: why gravity is different

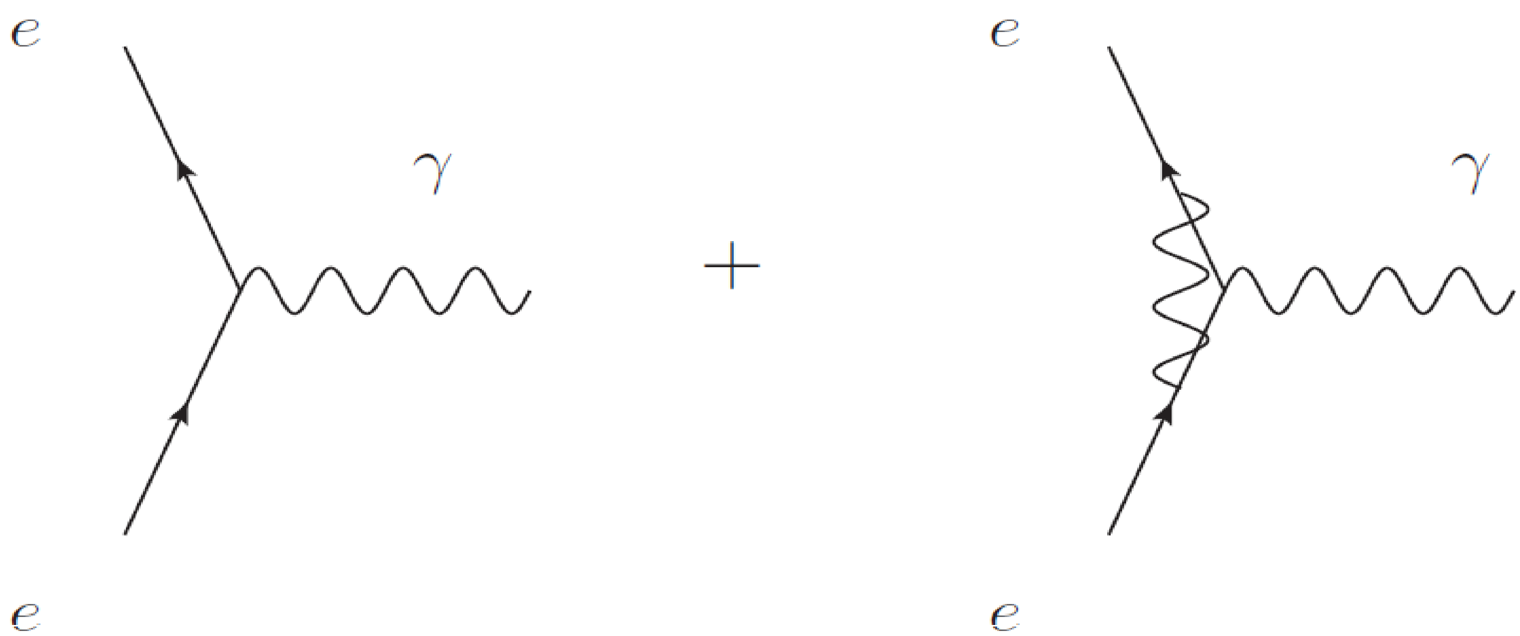
There are four fundamental interactions in nature :

Interaction	Description	distances
$Gravitation$	$Rel.\ gen.$	$Infinity$
$Electromagn.$	$Maxwell$	$Infinity$
$Strong$	$Yang-Mills\ (QCD)$	$10^{-15} m$
$Weak$	$Weinberg-Salam$	$10^{-17} m$

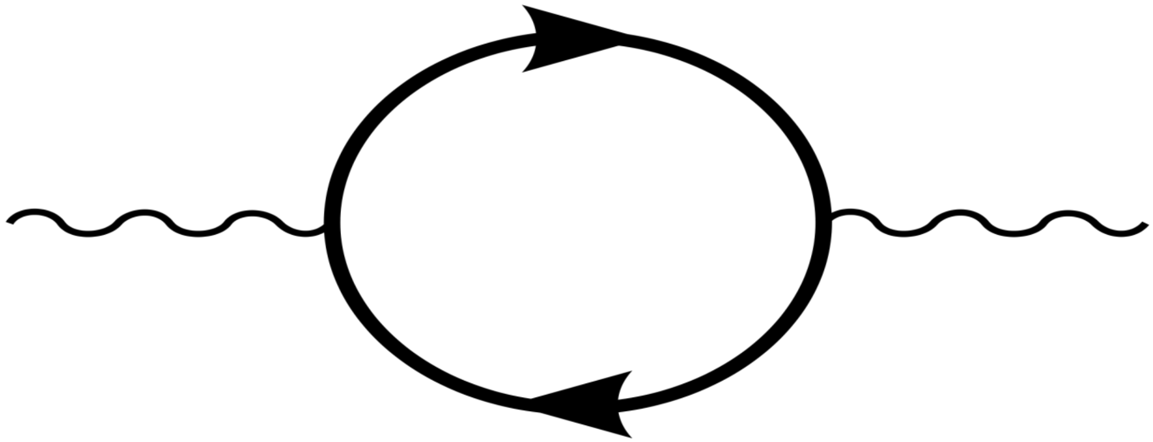
With the exception of gravity, all other interactions are described by renormalizable quantum field theories (QFT).

QFT = relativity + quantum mechanics

Computation of physical obervables is based on perturbation theory:



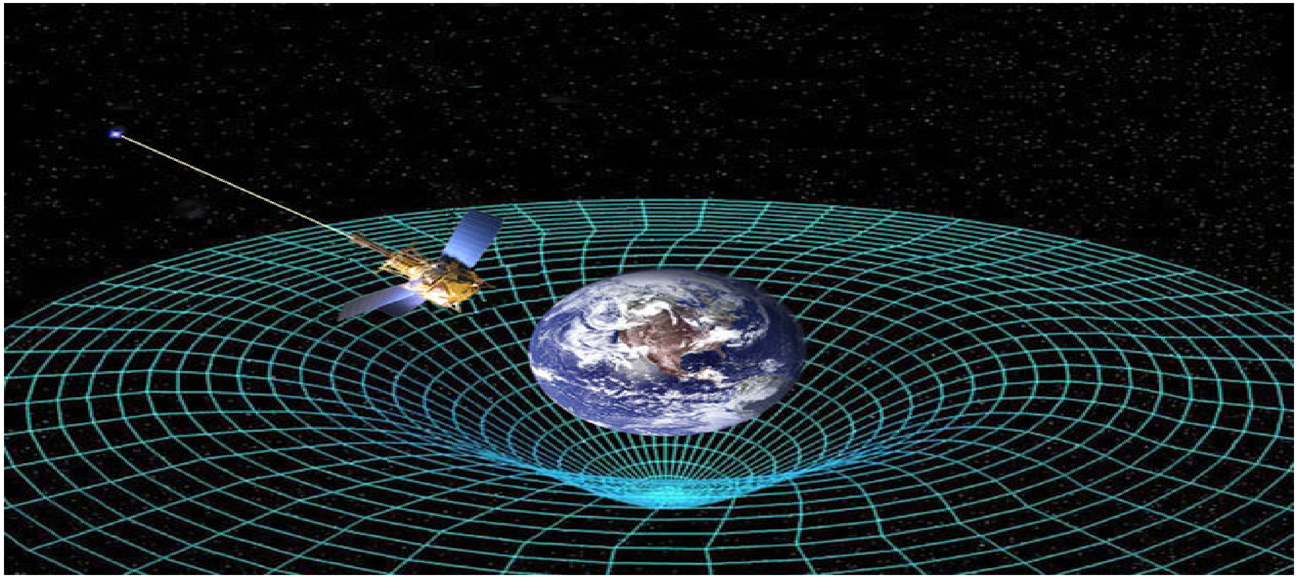
Point-like interactions in Feynman diagrams generate ultraviolet (UV) divergences



- Renormalizable theory: the UV divergences can be « hidden » into a finite number of parameters (charges,masses)
- Renormalization predicts the variation with energy of the fine structure constant, confirmed at CERN.

Einstein general relativity is a classical theory :

Mass/energy → spacetime geometry $g_{\mu\nu}$



Its quantization $g_{\mu\nu} = \eta_{\mu\nu} + \frac{1}{M_P} h_{\mu\nu}$ leads to UV divergences which cannot be reabsorbed in a finite number of parameters → non-renormalizable

The coupling of gravitational interaction is

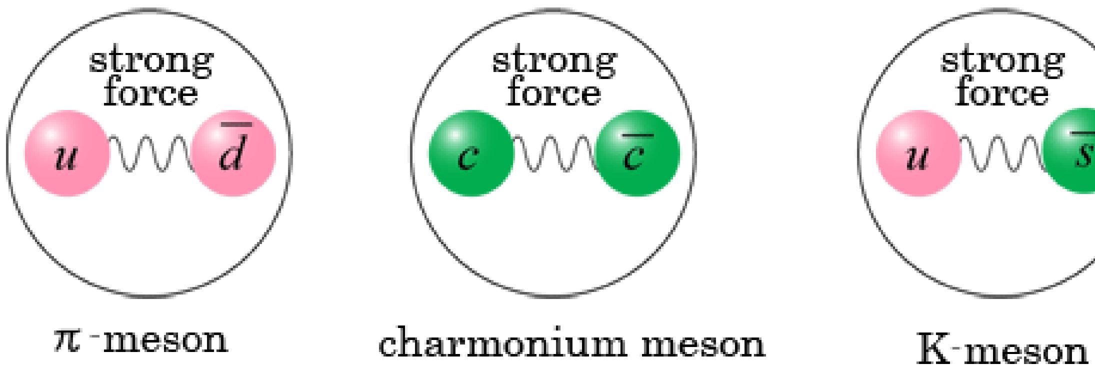
$$\frac{E}{M_P}$$

⇒ negligible quantum corrections at low energy.

At high-energies $E \sim M_P$ or in strong gravity fields, theory of quantum gravity is necessary.

2) String Theory: from strong interactions to gravity

- 1964 – Gell-Mann proposes quarks as constituents of hadrons, through the « colored » strong interactions



Quarks are « confined » into hadrons by forces increasing with distance. Mesons are strings of color with quarks at their ends.

- 1967-1968 : Veneziano, Nambu, Nielsen,Susskind :

Properties of the hadronic interactions well described by string-string interactions.

- Classical strings ⇨ vibrational modes $\omega_n^2 = n M_s^2$

- Quantum strings ⇨ particles $M_n^2 = n M_s^2$, with

string mass scale $M_s \sim GeV$

Hadrons are the vibrational modes of the quantum strings.

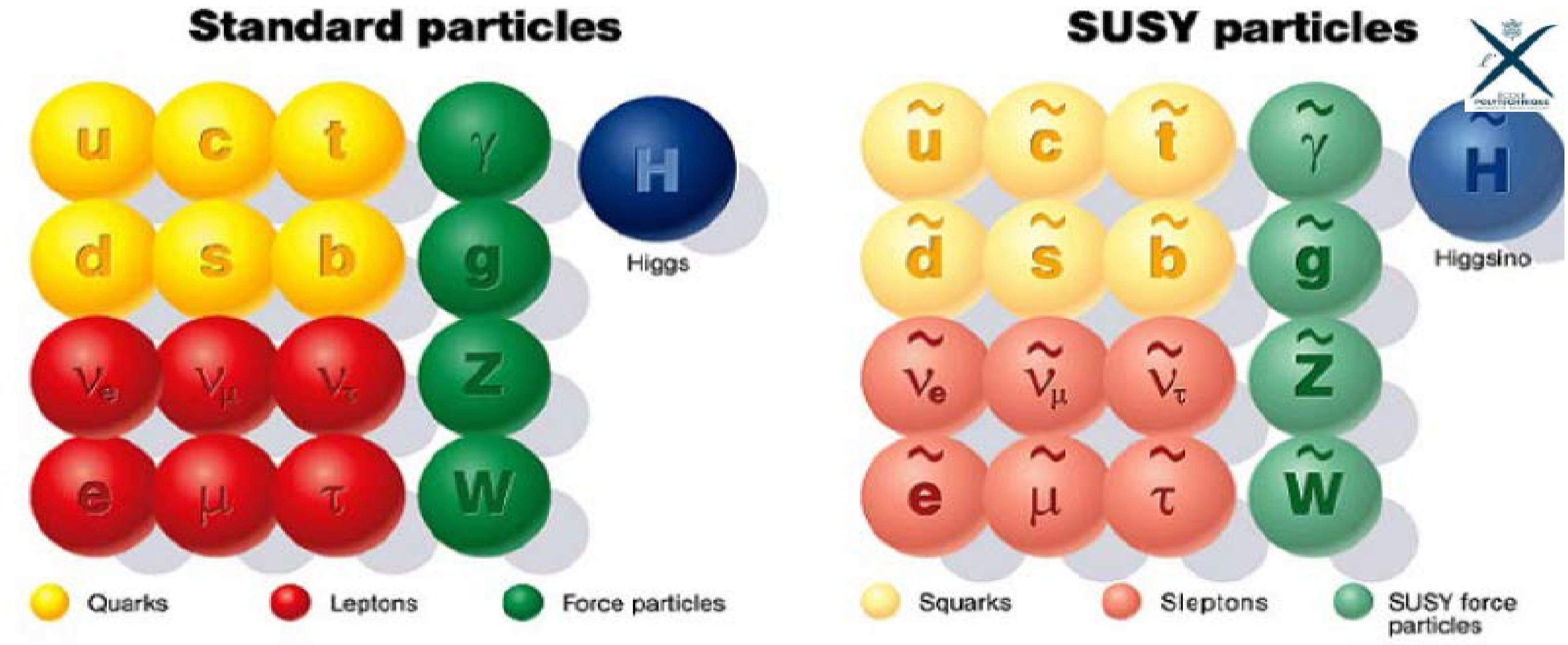
Some problems of the hadronic strings:

- Consistency conditions ⇒ 22 additional space dimensions.
- All string excitations are bosonic.
- Instability: tachyonic scalar ($M^2 < 0$) in the spectrum.
- In addition to gauge bosons (spin 1), a massless spin-two particle.

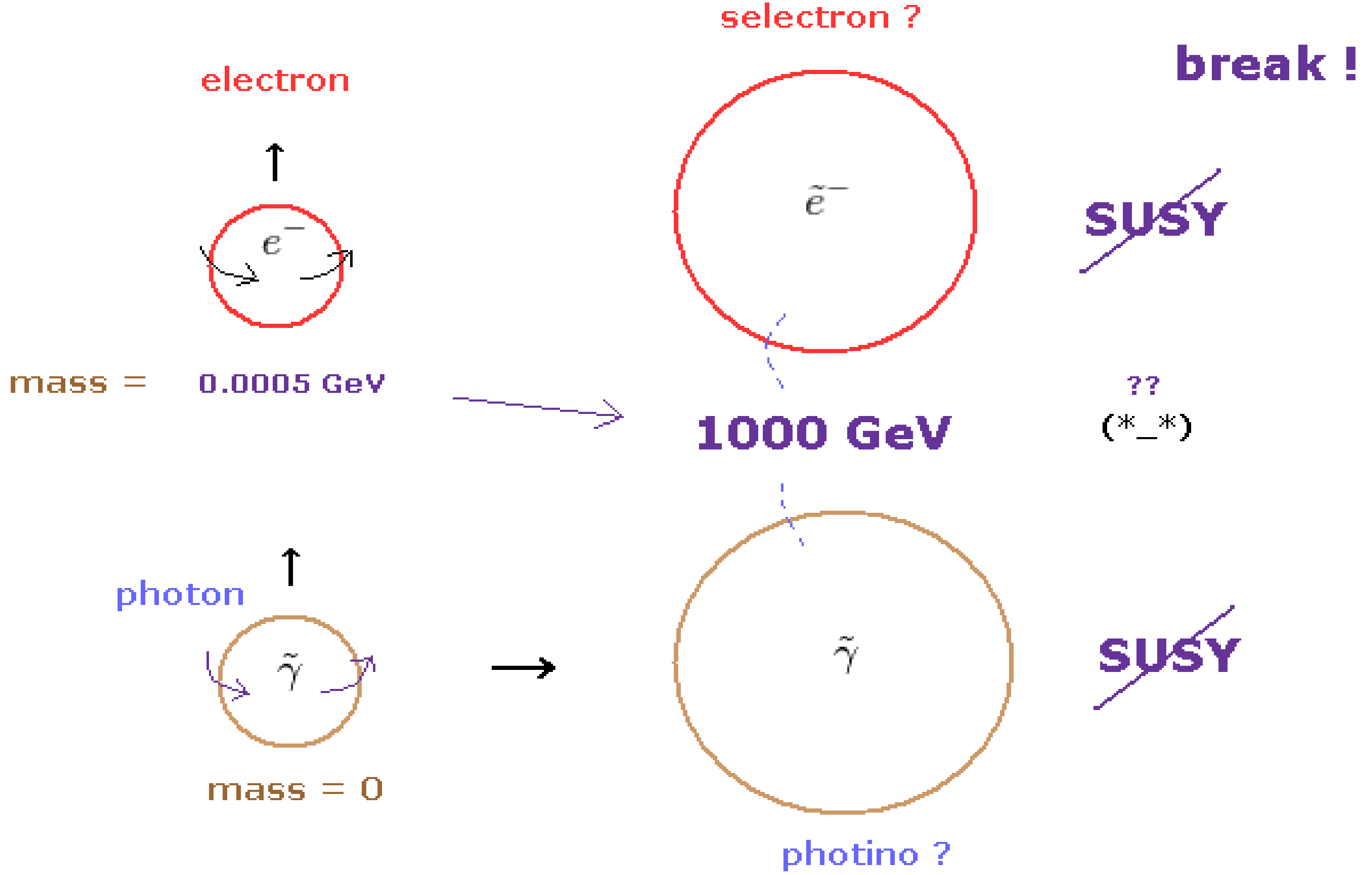
(Partial) solution of the first two problems : enlarge the symmetry of the theory :

Supersymmetry ⇒

- equal number of bosons and fermions (superstrings)



Supersymmetry has to be broken.
A central problem for String Theory. .



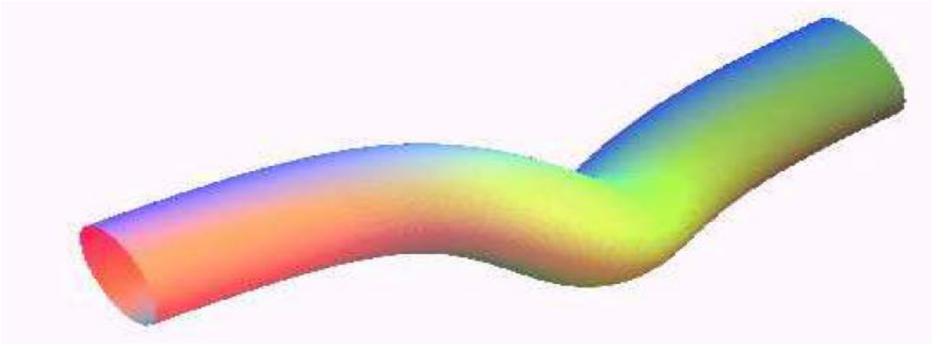
- six additional space dimensions

- 1974 (Scherk-Schwarz) : the interactions of the spin 2 particle is that of the graviton in general relativity !

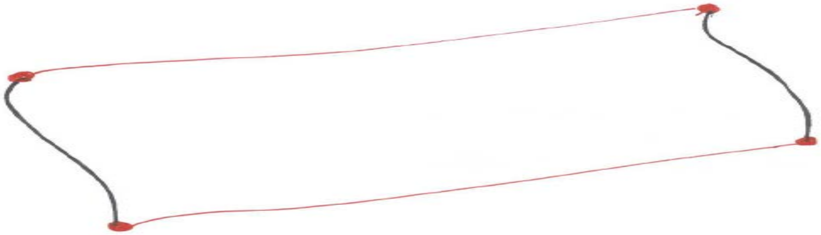
The zero mass spectrum of superstrings contains matter particles (fermions,scalars) and the mediators (bosons of spin 1 and spin 2) of all four fundamental interactions !

There are two type of strings:

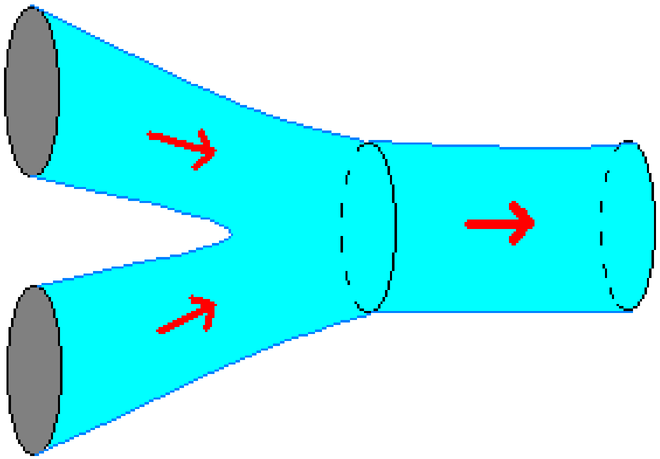
- Closed. Excitations: gravitons



- Open. Excitations: photons (gauge fields), electrons, etc



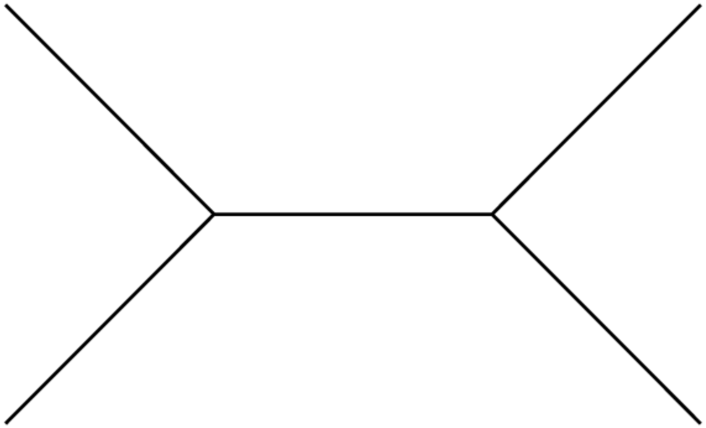
- Strings have no point-like interactions (minimal length $l_s = M_s^{-1/2}$)



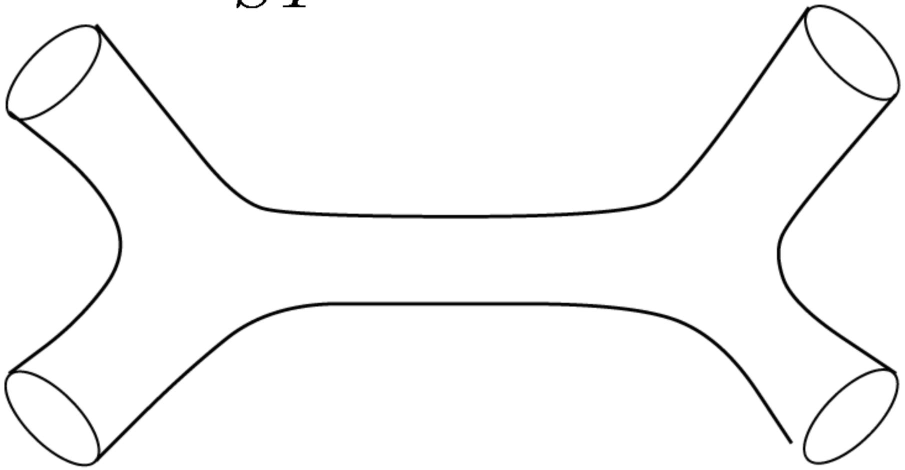
⇒ no UV divergences.

On the contrary, high-energy limit of string interactions (at fixed scattering angle) is much softer than in field theory

$$\sigma_{FT} \sim \frac{1}{s}$$



$$\sigma_{ST} \sim e^{-\frac{s}{M_s^2}}$$

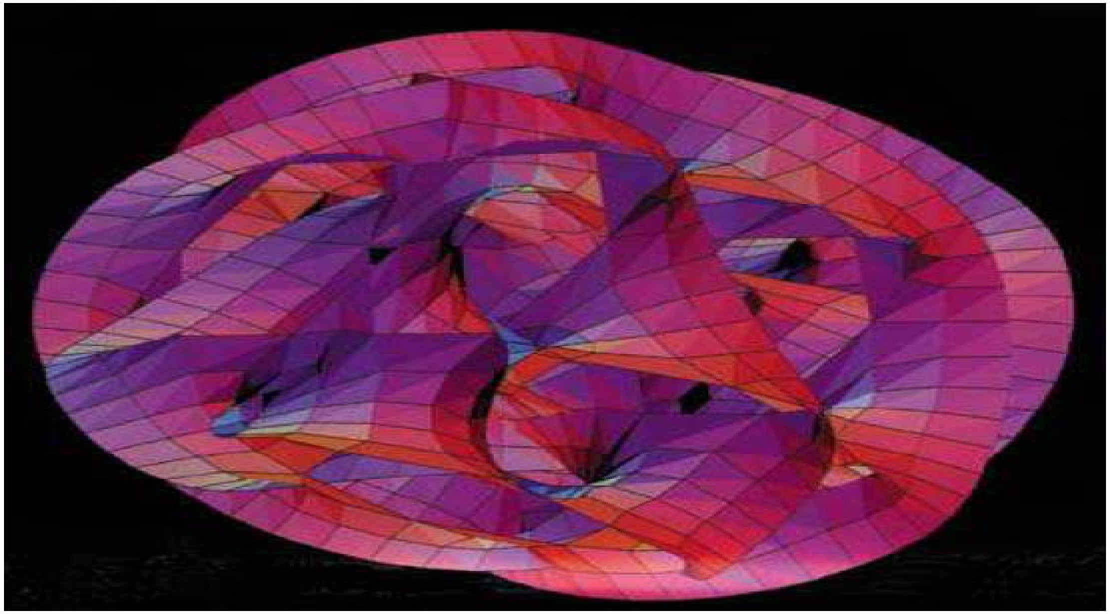


1984-1986 (Green-Schwarz ; Witten and coll, Gross and coll) : understanding of the

- consistency conditions,
- compactication
- generation of chiral fermions in four dims.

⟺

topological properties of the compact six-dim. internal space



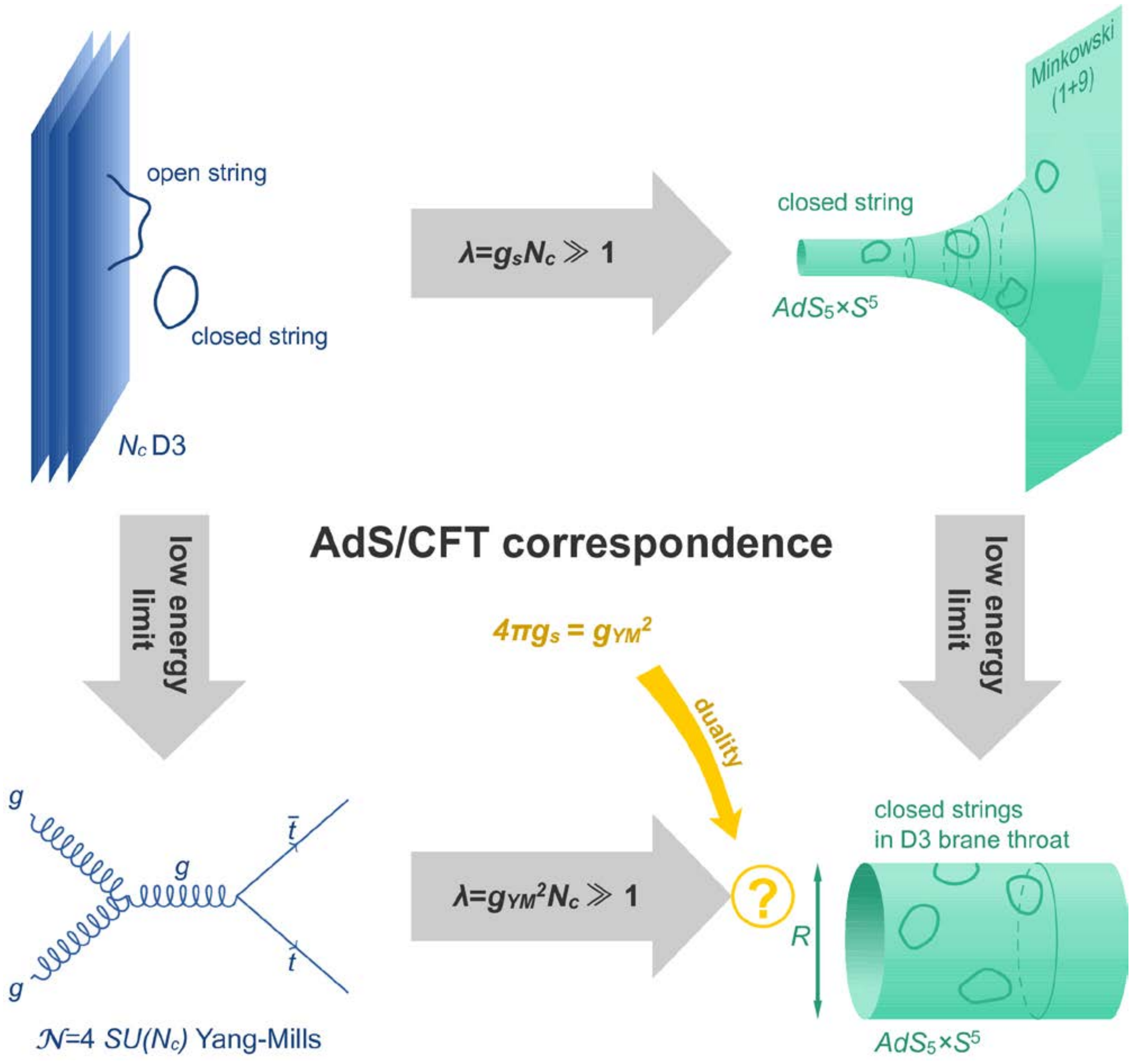
1997-1998 (Maldacena ; Gubser,Klebanov,Polyakov, Witten) :

Holographic duality

field theory in 4d — string theory in 10 dims
strong coupling — weak coupling
on $AdS_5 \times X_5$

This allows for a study of a strongly coupled 4d field theory with resonances in terms of a perturbative gravity theory in a higher dimensions.

Usually only the AdS_5 factor is important ⇒ five-dimensional gravity theory on a warped space.


open string
closed string
N_c D3
$\lambda = g_s N_c \gg 1$
closed string
$AdS_5 \times S^5$
Minkowski (1+9)
AdS/CFT correspondence
low energy limit
low energy limit
$4\pi g_s = g_{YM}^2$
duality
g
g
g
$\bar{t}$
t
$\mathcal{N}=4$ $SU(N_c)$ Yang-Mills
$\lambda = g_{YM}^2 N_c \gg 1$
?
R
closed strings
in D3 brane throat
$AdS_5 \times S^5$

3) Extra dimensions and Kaluza-Klein unification

The electromagnetic interaction and gravity can be described in a unified manner starting from Einstein gravity in 4 + 1 dimensions

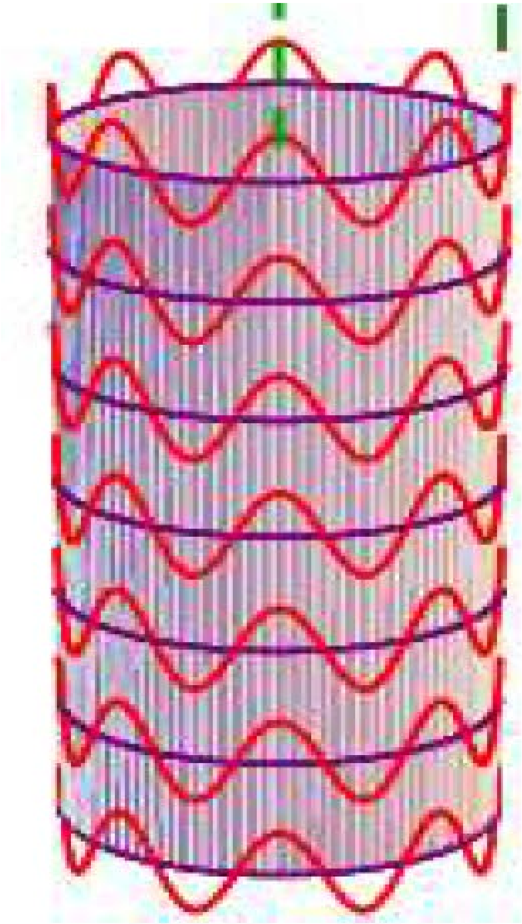
(Nordstrom,1914 ; Kaluza,1921)

five dimensions | four dimensions

g_{MN} | $g_{\mu\nu}$, $A_\mu = g_{\mu 5}$, $g_{55} = \Phi^{2/3}$

(graviton) | (graviton) photon scalar

- if the new space dimension is infinite, the gravity attractive force is $F \sim \frac{m_1 m_2}{r^3}$ instead of $F \sim \frac{m_1 m_2}{r^2} \Rightarrow$ needs to compactify the extra dimension



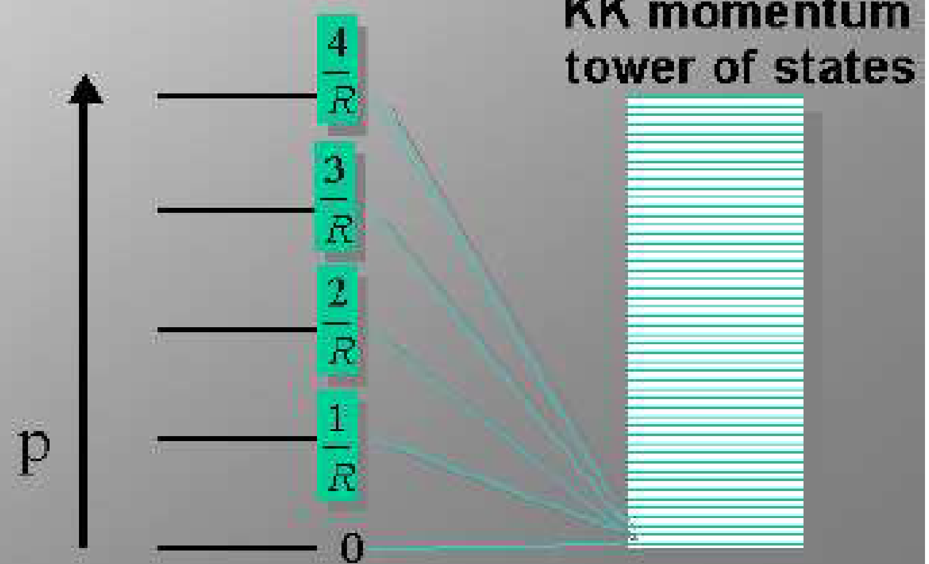
Kaluza-Klein modes

if spatial dimension is compact then momentum in that dimension is quantized:

$$p = \frac{n}{R}$$

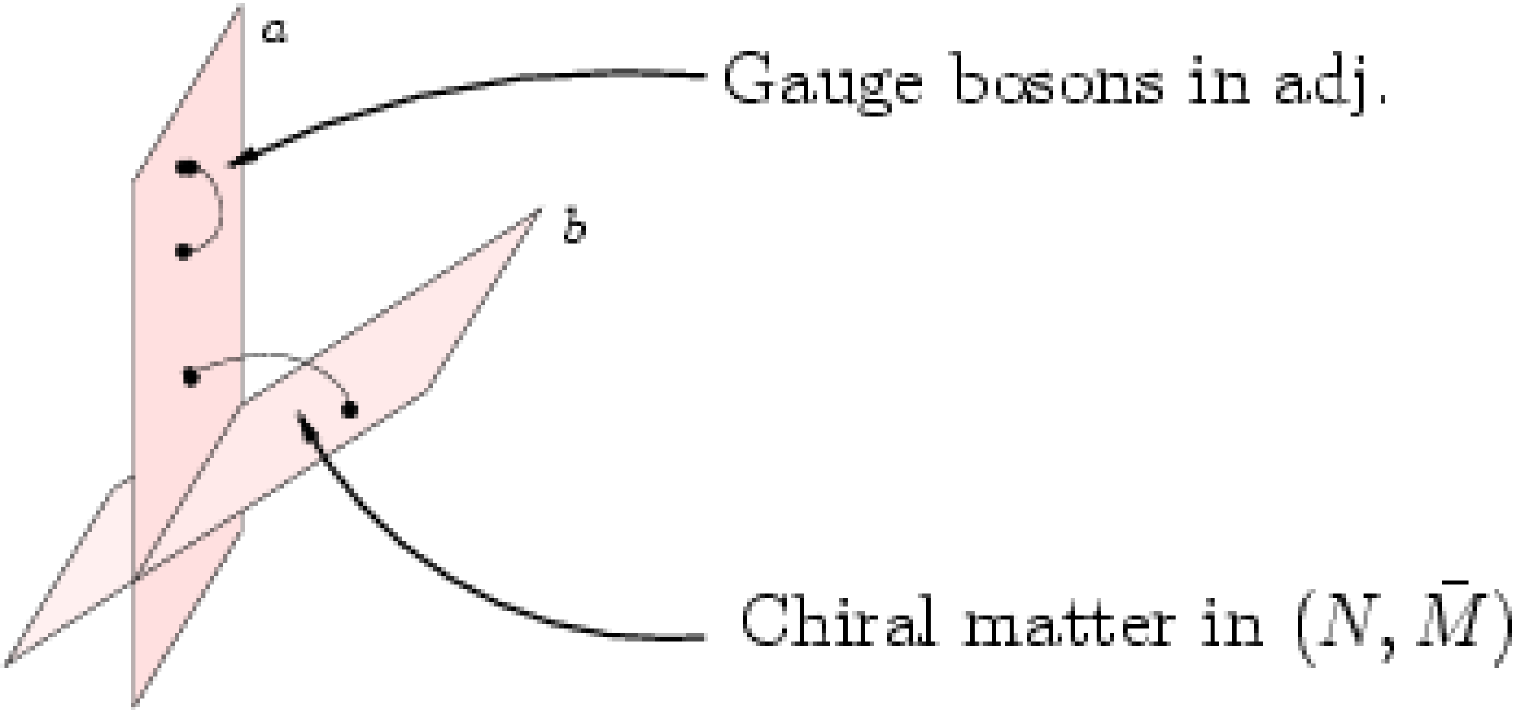
from our point of view we see new massive particles!

$$m^2 = m_0^2 + \frac{n^2}{R^2}$$



4) D-branes and brane-world models

String Theory has hyper-surfaces of p space dims. called Dp-branes, which contain gauge and matter fields



Dp-branes have mass T_p
and carry charges q_p

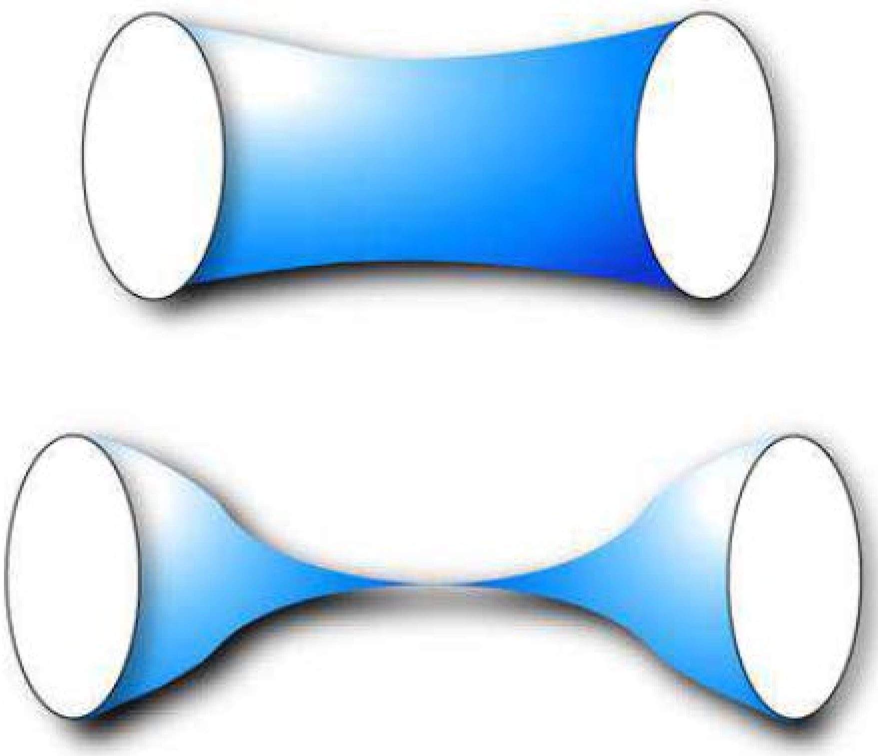
SUSY D-branes : mass=charge $T_p = q_p$

Charge neutrality in internal space ⟹

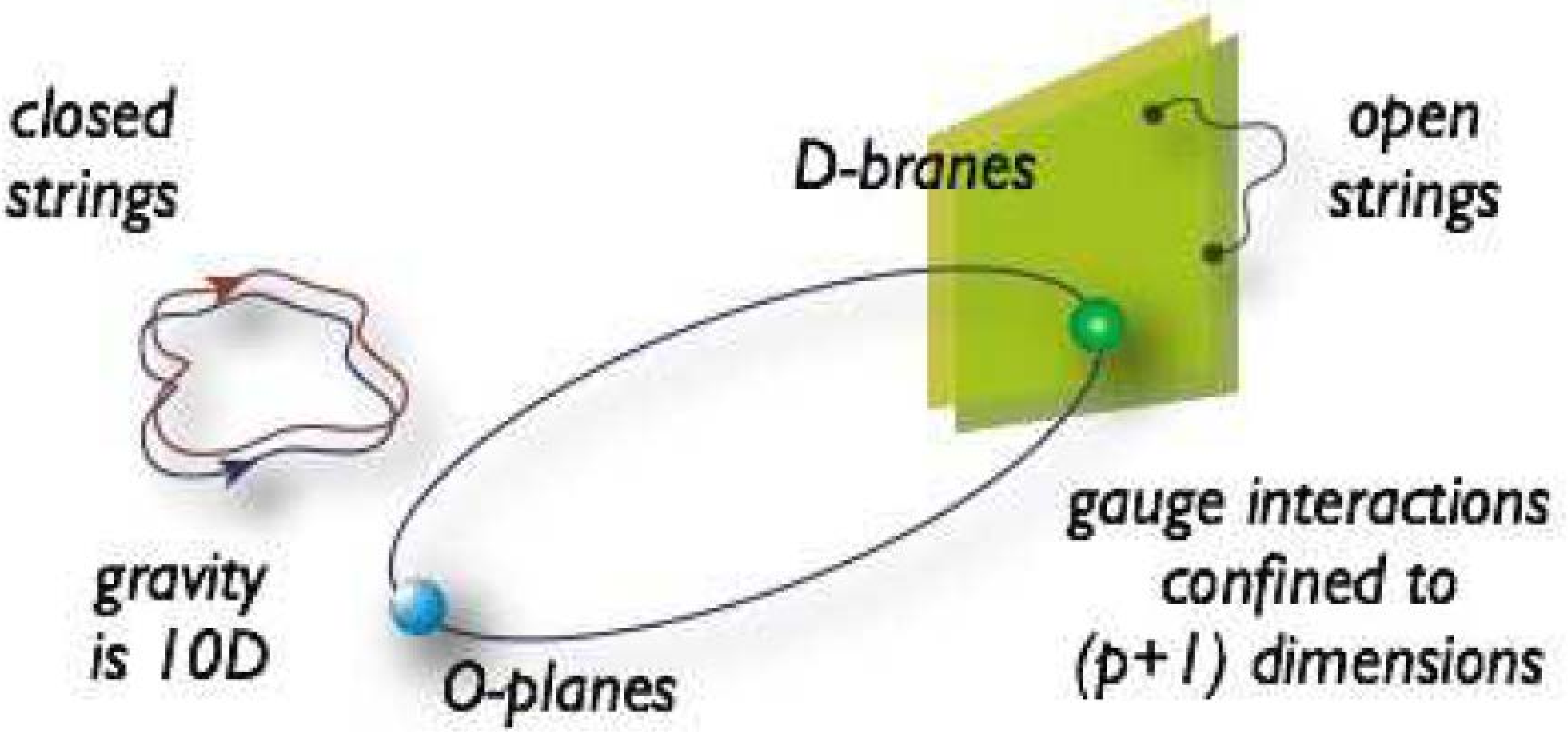
non-dynamical localized objects (mirrors) of
negative mass and charge : O-planes

Crucial constraint: RR tadpole constraints ⟺
UV finiteness ⟺ Gauss law in internal space

$$\sum_{Dp} q_{Dp}^{(n)} + \sum_{Op} q_{Op}^{(n)} = 0$$

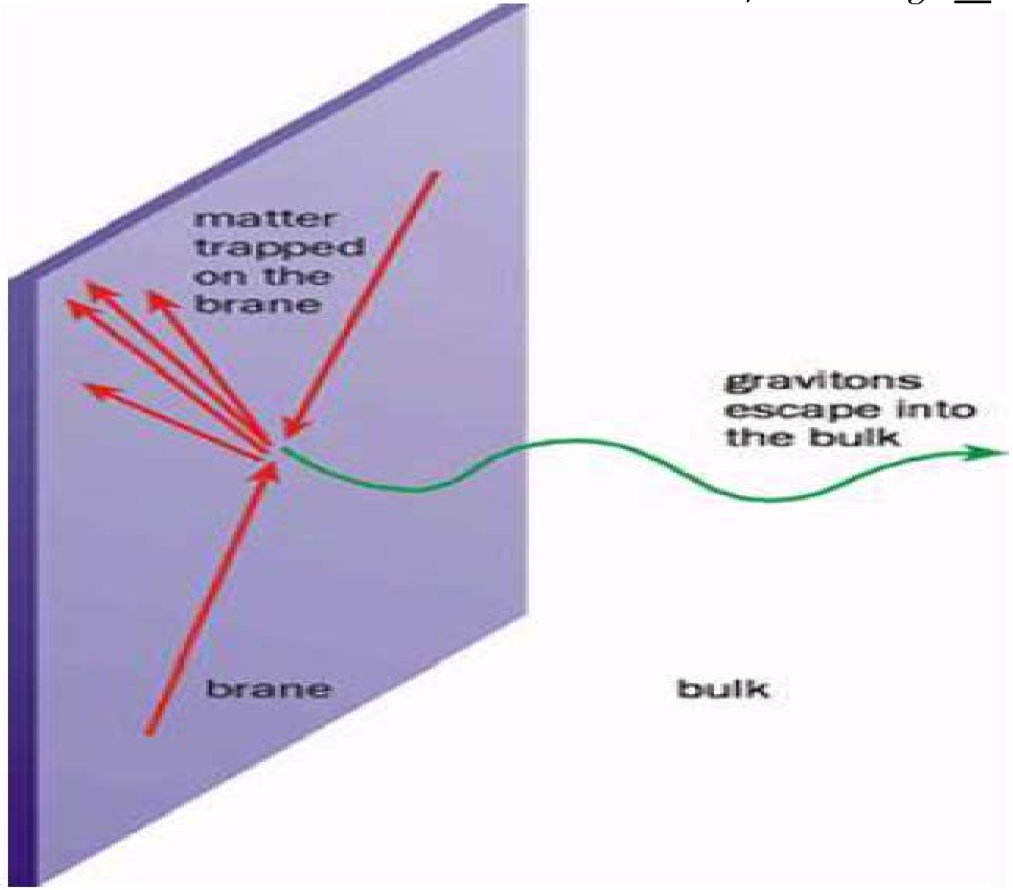


Cartoon picture of a string model



Brane-world models :

- The Standard Model is localized on a D-brane
- Gravity propagates into the bulk of 10d space
- Fundamental scale $M_* \sim M_s \geq 10\ TeV << M_P$



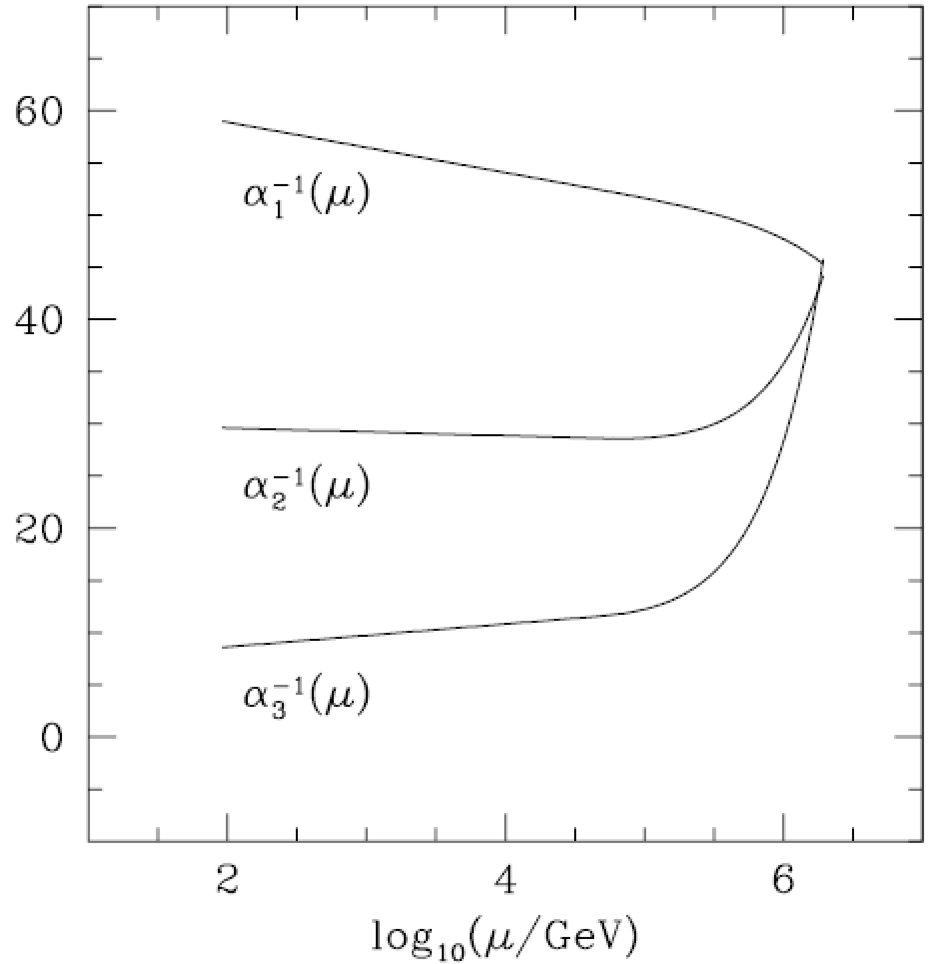
There are two types of extra dimensions:

- perpendicular (to our D-brane world)

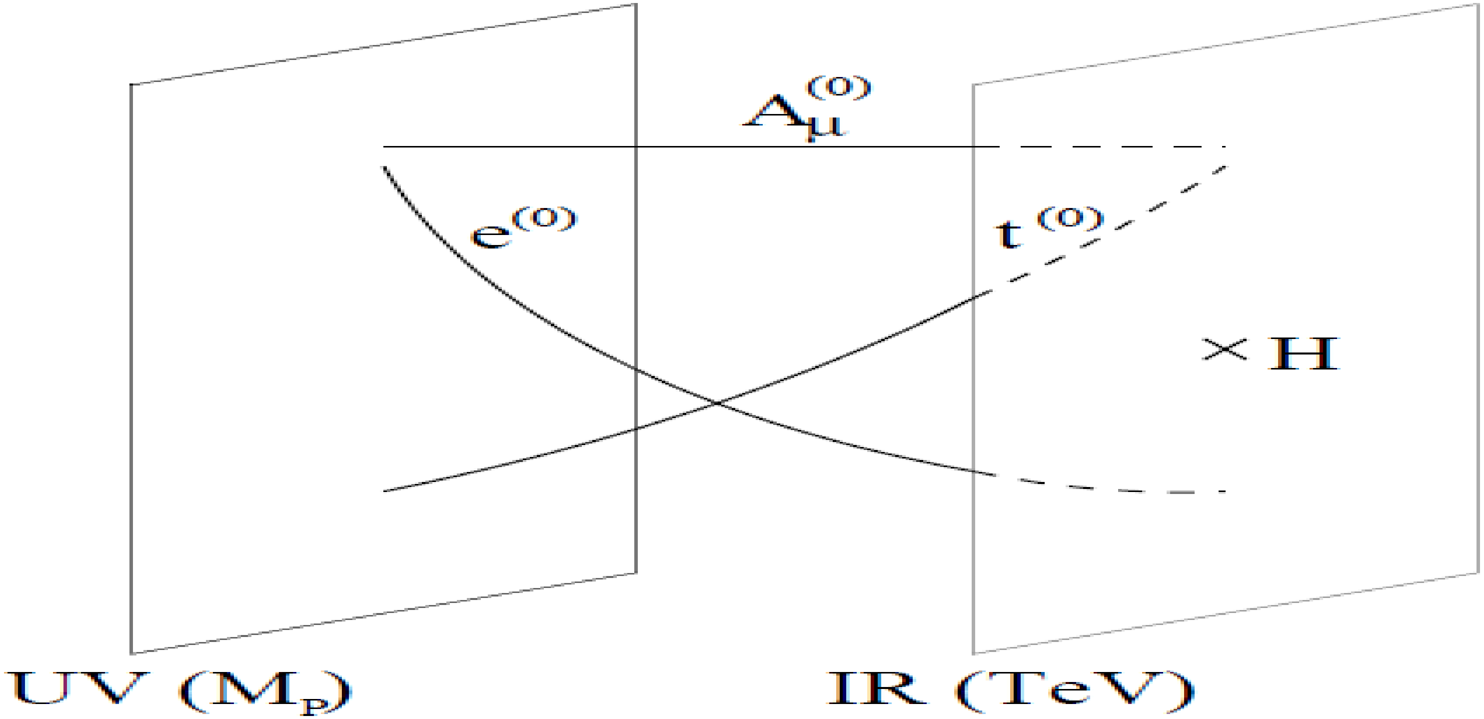
Only gravity propagates ⟹ experimental constraints come mainly from deviations from Newton law : $R_{\perp} < 0.1 \; mm$

Parallel dimensions: photons,electrons propagate : tighter constraints: $R_{||} < 10^{-15}\ mm$

- KK states can be produced at colliders
- They can trigger unification at low-energy
- Dark matter candidate (lowest KK particle)



There was an intense activity in constructing holographic extensions of the Standard Model



Holographic « dictionary »:

- States localized on the UV brane are elementary
- States localized on the IR brane are composite (resonances) of a strongly coupled sector.

5) Conclusions

- String theory: fascinating journey into the quantum structure of gravity.
- It evolved from a theory of hadrons to a theory unifying all fundamental interactions.
- With the advent of holography, it became again a tool to study strong interactions.
- Large extra spacetime dimensions

string theory at a low scale M_s ⟹ spectacular effects:

- Regge states
- unification at low energy
- submm dims.

Supersymmetry breaking still a major issue .

Thank you

Backup slides

Large literature on SUSY non-linear realizations and low-energy goldstino interactions

- Volkov-Akulov, Ivanov-Kapustnikov
- - Siegel
- Casalbuoni, Dominicis, de Curtis, Feruglio, Gatto
- Brignole, Feruglio, Zwirner; Brignole
- Komargodski and Seiberg (KS)...